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Geometric Singularities, Moduli Stabilization, and Gravitational Wave Signatures in String Compactifications

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We present a unified framework connecting Calabi–Yau geometry, singularity theory, and early-universe cosmology within heterotic and Type IIB string compactifications. Starting from the Tian–Yau threefold defined by its complete-intersection configuration matrix P^3 [3 0 1] P^3 [0 3 1], we demonstrate how a free $\mathbb{Z}_3$ quotient reduces the Euler characteristic to $\chi = -6$, yielding precisely three chiral generations. By embedding a stable $SU(4)$ vector bundle with $c_1(V) = 0$ and $c_2(V) = 12 \leq c_2(TX) = 50$, we satisfy the Green–Schwarz anomaly cancellation condition while preserving $N = 1$ supersymmetry and enabling Wilson-line breaking of E_6 to the Standard Model gauge group.

A central result is the identification of universal singularity structures governing vacuum transitions. Generic multi-field scalar potentials correspond to non-simple singularities with Milnor number $\mu = 9$, but near critical degeneracy loci the Hessian vanishes and the system universally reduces to an A_2 cusp with $\mu = 2$ [1]. This reduction controls the dynamics of first-order phase transitions in the early universe. We derive the stochastic gravitational-wave spectrum generated near these critical points, showing that potential flattening enhances the signal amplitude as $\Omega_{\text{GW}} \propto \delta^{-3}$, where $\delta = 1 - \hat{\xi}/\hat{\xi}_c$ measures the distance to criticality. The predicted peak frequencies naturally lie in the milli-Hertz band, and benchmark points satisfying strong first-order transition criteria yield $\Omega_{\text{GW}}h^2 \sim 10^{-12}$–$10^{-11}$, placing them directly within the sensitivity window of the LISA mission.

We systematically analyse the KKLT moduli stabilisation mechanism [2] incorporating leading α'^3 corrections to the Kähler potential. The correction breaks the classical no-scale structure and generates three distinct vacuum regimes separated by a critical threshold $\hat{\xi}_c$. For $\hat{\xi} < \hat{\xi}_c$, controlled AdS minima persist and can be uplifted to metastable de˜Sitter vacua; for $\hat{\xi} > \hat{\xi}_c$, the potential exhibits runaway behaviour characteristic of the Large Volume Scenario or decompactification. The conifold transition mechanism [3], where massless black holes resolve geometric singularities via flop transitions, provides a dynamical pathway connecting parent manifolds to the three-generation Tian–Yau/$\mathbb{Z}_3$ vacuum. We quantify the tension between shallow dS vacua near $\hat{\xi}_c$ and the de˜Sitter swampland conjecture, mapping the parameter space where controlled string constructions remain consistent with quantum gravity constraints. Detailed derivations, explicit benchmark tables, and the full Hessian analysis are provided in [1]. Our results establish a direct observational bridge between compactification topology, singularity-driven cosmology, and gravitational-wave detectors.
Keywords: String compactification, Tian–Yau threefold, conifold transitions, singularity theory, Milnor number, KKLT mechanism, α'^3 corrections, gravitational waves, LISA, de˜Sitter swampland conjecture.

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